Inversion of Crosswell Seismic Data: Beyond the Black Box

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Summary

We present a new method to invert crosswell seismic data. The method uses low-wavenumber velocity information from direct arrivals and high wavenumber velocity information from stacked, true amplitude crosswell reflection images. The technique is unlike conventional 'black-box' full-waveform crosswell inversion techniques in that it does not operate on the raw, or minimally processed crosswell seismograms. The inversion results tie with sonic logs and do not exhibit artifacts commonly associated with tomography.

Introduction

For many geoscientists in the oil industry, the holy grail of seismic imaging is high resolution delineation of reservoir porosity, permeability and fluid distributions. Crosswell seismic techniques have been used to provide both high resolution (on the order of 2 m vertical resolution) qualitative images through the use of reflections (e.g. Lazaratos, et al,1995) and robust, relatively low resolution estimates of formation velocity through the use of traveltime tomography. Surprisingly, there has been only one published attempt (Bashore, et al, 1994) to invert the imaged crosswell reflection data using conventional surface seismic inversion techniques. Crosswell reflection data is, in principal, much better suited to recursive or sparse spike inversion techniques because the frequency content is much higher than surface seismic frequency content, and there is less need to recover out-of-band components. In addition, the crosswell direct arrival can be used to produce a low frequency component (i.e. the tomogram) for the inverted image. With surface seismic data, the low frequency component is typically incorporated through less-reliable stacking velocities. Moreover, the crosswell direct arrival can be extracted to yield a deterministic seismic wavelet Wavelet estimation is a critical component in inversion and is often a poorly-constrained component of surface seismic inversion.

Instead of inverting the imaged crosswell reflection data using a surface-seismic-like approach, most studies aimed at producing a quantitative, high resolution image from crosswell data have used what we term a 'black box' approach. In a 'black box' approach the raw, or minimally processed crosswell data are inverted using diffraction tomography (e. g. Dickens, 1994, Harris and Guan, 1996) or full waveform inversion algorithms (e. g. Zhou, et al, 1995). While these approaches have the potential to produce high resolution quantitative images of the interwell region, many formulations do not incorporate the complexities of the crosswell wavefield. For example, many diffraction tomography algorithms assume an acoustic wavefield, yet the wide-angle nature of crosswell data requires an elastic approach unless substantial wavefield separation is performed in advance. Additionally, most inversion algorithms do not incorporate borehole effects which include tube waves and dramatic amplitude and radiation pattern effects (Peng, et al, 1994 and Rector and Lazaratos, 1994). The published literature seldom attempts to quantitatively correlate the images with log or core properties.

In this paper we describe a simple waveform inversion method for crosswell reflection data that is more similar to surface seismic impedance inversion than to 'black-box' inversion techniques previously published. Our technique uses direct arrival traveltimes to estimate the low frequency velocity field and reflection amplitudes to estimate the high frequency interwell velocity field. The data used to test our inversion approach come from the Mcelroy experiment (Harris, et al, 1995). Over 35,000 traces from a piezoelectric source and hydrophone receivers were acquired between 2600 and 3150 ft at 2.5 ft source and receiver sampling intervals. The data were processed using wavefield separation and VSP-CDP mapping (Rector, et al, 1995, Lazaratos, et al, 1995) without amplitude compensation to produce a P-wave reflection image (shown in Lazaratos, et al, 1995).

Although the reflection data was not considered to be a true amplitude image, the interwell reflection image was processed by Bashore, et al (1994) to produce a quantitative interwell impedance model. To produce the impedance model the P-wave reflection image was converted into a balanced reflectivity section and inverted for impedance using a sparse spike algorithm. The impedance was integrated with a low frequency impedance model derived by interpolating the log-derived impedance between the boreholes. The tomogram was not incorporated into the inversion due to artifacts. The low frequency impedance model was used over a wide range of wavelengths (from DC to about 30 ft). The principal contribution of the reflection image to the inversion was in the very short wavelength range (from 5 to 30 ft). Consequently, the final inversion results are heavily biased toward the log-derived components. Our work differs from Bashore et al (1994) in several ways. First, we use a true amplitude reflection image for input into the inversion rather than the balanced reflectivity used by Bashore, et al, (1994). Second, we use a recursive algorithm rather than a sparse-spike algorithm. Third, we invert directly for velocity rather than impedance. Finally, our inversion results are not obtained with the use of any log-derived velocities.

Crosswell Seismic Inversion

Inversion of Crosswell Reflection Data

The principal steps in the inversion were:

- Reflection imaging using amplitude-compensated wavefield separation to isolate primary reflections and reflection mapping using a modified VSP-CDP transformation (Lazaratos, et al, 1995)
- Image correction (applied to the VSP-CDP mapped and stacked data) for borehole amplitude effects
- Recursive inversion of the amplitude-corrected reflection image to produce P-wave velocities and incorporation of low wavenumber velocities through P-wave direct arrival times.

Wavefield separation was used to isolate and enhance the primary reflections and attenuate coherent interference such as tube waves, conversions, shear waves, diffractions, and multiples. In this study, we retained relative amplitudes by configuring the wavefield separation filters so that the reflection amplitudes were unaltered by the application of a wavefield separation filter. In practice, this amplitude preservation step consisted of equalizing the data prior to the application of a particular wavefield separation filter, saving the equalization parameters in a database, and then deapplying the equalization factors after wavefield separation. The wavefield separation filters were also configured to have unit gain within the spatial and temporal passband. We mapped the wavefield separated reflection images into common reflection point bins using the same velocity field used in (Lazaratos, et al, 1995). For each common reflection point we stacked reflection incidence angles between 20 and 60 degrees. We did not use angles above 60 degrees because these wide angles tend to occur at traveltimes that have substantial amounts of coherent noise in the form of head waves, conversions, and guided waves. Figure 1 shows the unbalanced reflection image.

Amplitude Correction

At the Mcelroy site Rector and Lazaratos (1995) found that the quasi-static model for borehole coupling (Peng, 1994) accurately predicted average P and S-wave direct arrival amplitudes provided that Zoeppritz-related transmission effects were incorporated. The quasi-static model uses the source-takeoff and receiver-incidence angle of the particular ray along with the properties of the formation adjacent to the borehole, casing, and borehole fluid to predict the arrival amplitude. The quasi-static model predicts that the amplitude of body wave arrivals radiated and received by fluid-coupled sources and receivers are frequency independent, but can vary dramatically as a function of shear wave velocity and takeoff/reception angle.

To model the amplitude effects in the VSP-CDP mapped and stacked reflection image, we mapped and stacked a scalar dataset produced by raytracing reflection arrivals and computing takeoff and incidence angles as a function of arrival time and source and receiver depth. Time-dependent scalar traces were produced from the arrival times and takeoff/reception angles using the quasi-static model (model parameters obtained from the mapping velocity function) for borehole effects. In addition, spreading and transmission effects were incorporated. We then mapped and stacked the scalar traces exactly like we mapped and stacked the real data (excluding incidence angles below 20 degrees and above 60 degrees).

Figure 2 shows the mapped and stacked scalar image. The effects of coupling and transmission create vertical and lateral variations in the reflection amplitude of nearly a factor of 3. Without these corrections, it is clear that subtle reflection amplitude effects may be obscured. To correct for coupling and transmission losses, we divided the reflection image in Figure 1 by the scalar image in Figure 2. The depth and time varying result of this scaling represents our best effort at generating a borehole-corrected true amplitude reflection image.

Inversion

A standard approach to producing an impedance image from a 'true amplitude' reflection seismogram is the use of a recursive algorithm or a sparse spike algorithm that recovers impedance and, in the case of the sparse spike algorithm, attempts to extend the bandwidth of the reflection seismogram beyond the bandwidth of the recorded data using a model for the reflectivity function (sparse delta functions). While these algorithms differ in their estimation of out-of-band frequency components, they both assume that the P-wave pressure reflection coefficient, RC, is related to the impedance function through the equation:

$$RC = \rho 2V2-\rho 1V1/(\rho 2V2+\rho 1V1). \qquad (1)$$

This equation is only valid for normal incidence. For the higher incidence angles present in crosswell reflection data (generally 40 to 60 degrees) the reflection coefficient becomes much simpler if we assume that the contrast in elastic moduli at the interface is small. The wide-angle P-wave reflection
coefficient can be written as a function of velocity and incidence angle:

$$RC_{\text{wide angle}} \sim DV(\tan^2\theta-\sin^2\theta)/2V \qquad (2)$$

Consequently,. impedance estimation r for near-normal-normal incidence angles becomes velocity estimation at wide angles provided that the mean reflection incidence angle for each interface is constant. This criteria is implicitly satisfied because to produce equation 2 the contrast in elastic moduli is assumed to be weak.

To verify equation 2 we generated synthetic seismograms from the P-wave velocity model used in the VSP-CDP mapping of the reflections. To estimate densities, we used Gardner's relations and a constant poissions ratio of 0.24 to generate S velocities. Synthetic seismograms were produced by convolving a 120 to 1000 Hz ricker wavelet with a spike reflection series produced using raytracing. The only amplitude effects incorporated in the modeling were reflection coefficients. transmission effects, geometric spreading were assumed to have been corrected for. We generated constant incidence angle synthetic seismograms at normal incidence, 30 degrees, 45 degrees and 60 degrees. Figure 3 shows these synthetic constant-angle seismograms. As predicted by equation 3, the wide-angle seismograms appear to be scaled versions of each other. They also appear to be quite similar to the normal incidence seismogram, indicating that density changes do not substantially affect the reflectivity function for this model.

We used a very simple recursion formulation to produce a velocity image from the crosswell reflection data shown in Figure 4. We integrated the true-amplitude reflection image and then added the velocity function used for VSP-CDP mapping as a low frequency component. To remove high frequency components from the VSP-CDP mapping velocity function we attenuated wavelengths less than 50 ft with a butterworth lowpass filter. The inverted velocity image contains wavelengths between DC and 5 ft, and therefore, is nearly comparable to having a sonic log along a line between the two wells. Since the data were not migrated, the lateral resolution of the 'pseudo sonic log is lower than the vertical resolution. For the incidence angles used in the image and the wavelengths recorded the horizontal Fresnel Zone is about 1/5 of the interwell distance (Lazaratos, 1993) or about 35 feet. The inverted reflection compares well with the sonic log at the two wells. The RMS error is about 2% and the maximum error is less than 10%. Some of the error may be due to errors in the sonic log-derived velocities rather than the crosswell-derived velocities.

Conclusions

By inverting true amplitude crosswell reflection data using a recursive time-domain approach, we reconstruct a high resolution image of the interwell velocity field. This approach is unlike conventional crosswell inversion algorithms and diffraction tomography algorithms in that it operates on the crosswell reflection image rather than on the raw data. Application of the inversion to real field data show a good correspondence to log velocities without the artifacts generally seen in diffraction tomography.

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